

The feasibility of low CO₂ concentration targets and the role of bio-energy with carbon capture and storage (BECCS)

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Received: 28 December 2009 / Accepted: 9 March 2010 / Published online: 19 May 2010
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Abstract The United Nations Framework Convention on Climate Change (UN FCCC 1992) calls for stabilization of atmospheric greenhouse gas (GHG) concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. We use three global energy system models to investigate the technological and economic attainability of meeting CO₂ concentration targets below current levels. Our scenario studies reveal that while energy portfolios from a broad range of energy technologies are needed to attain low concentrations, negative emission technologies—e.g., biomass energy with carbon capture and storage (BECCS)—significantly enhances the possibility to meet low concentration targets (at around 350 ppm CO₂).

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1 Introduction

Over the last few years, a wide range of mitigation scenarios has been published that look into the technology mix that is consistent with certain climate targets. What atmospheric GHG concentration level humankind ought to strive for in order to meet the UNFCCC target is a value-laden question. On the “ambitious” side, several scientists (Azar and Rodhe 1997; Graßl et al. 2003; Hansen 2005; Rockström et al. 2009) and governments (European Council 2005; MEF 2009) have argued that setting the target for global temperature increase at around 2°C above pre-industrial levels or even lower may be required. A 2°C target translates into long-term greenhouse gas targets that lie in the range of 450 parts per million (ppm) CO₂-eq (20–70% probability), 400 ppm (40–90%) or even lower (Meinshausen et al. 2006).

In terms of CO₂ concentration, this corresponds to concentration 400 ppm for a climate sensitivity of 3 degrees per CO₂ equivalent doubling (if the climate sensitivity is as high as 4.5 degrees per CO₂ doubling, the required CO₂ concentration falls below 350 ppm, if the climate sensitivity, on the other hand is as low as 2 degrees per CO₂ doubling, the two degree target can be met even if atmospheric CO₂ concentrations reach 500 ppm, see Azar and Rodhe 1997).

Meeting CO₂ stabilization targets below 400 ppm implies that global net CO₂ emissions will eventually have to be reduced to near zero or may even need to become negative (Azar et al. 2006; Fisher et al. 2007; Knopf et al. 2009; Riahi et al. 2007; van Vuuren et al. 2007). Negative emissions can be generated by several techniques, including reforestation, direct air capture, and the combination of bio-energy and carbon-capture-and-storage in power plants (BECCS; Obersteiner et al. 2001). The latter technique has now been used in several scenario studies (including the ones quoted above); in general, these studies show that the technique does make low-targets considerably more attainable. Still, there is an ongoing scientific debate on whether targets in the order of 450, 550 and even 650 ppm CO₂-eq can be achieved—and what exact role different technologies, including BECCS may actually play in this. This debate was already ongoing in the early 2000s, (Hoffert et al. 2002; Pacala and Socolow 2004), but has continued since then (Azar et al. 2006; van Vuuren et al. 2007). Interestingly, no studies to date have compared the impacts of including BECCS across different models.

In this paper, we briefly explore the contribution of BECCS, as a feasible negative carbon emission technology, to the attainability of stabilization targets below what has been perceived as the lower bound for atmospheric CO₂ concentrations for three different global energy models. These are IMAGE/TIMER (Bouwman et al. 2006; van Vuuren et al. 2007; De Vries et al. 2002), GET (Azar et al. 2003, 2006), and MESSAGE (Rao and Riahi 2006; Riahi et al. 2007; Schrattenholzer et al. 2004).

2 Methods

The role different technologies can play strongly depend on their context. While different publications have emphasized that including BECCS can make low stabilisation target more attainable, no attempt has been made to compare this across different models. For this reasons, the current publication looks into the influence of including BECCS and CCS in three different models, i.e. IMAGE/TIMER, GET

and MESSAGE, specifically looking into the attainability of low greenhouse gas concentration targets. All three models have an explicit representation of technology (as required in order to show the influence of BECCS) and did publish earlier scenarios which included BECCS. At the same time, the models differ significantly with respect to assumed development for technologies and the abatement options considered.

The IMAGE/TIMER model is an integrated assessment model with considerable focus on a spatially explicit representation of land use and the carbon cycle. The TIMER model forms the energy component and represents the long-term dynamics of the production and use of about 10 primary energy carriers on the basis of depletion and technology development dynamics. Technologies in the model are selected in the model mostly using multinomial logit equations assigning a large market share to low costs options and a small market share to options with a higher costs (thus no full optimisation). MESSAGE is a dynamic linear programming model, calculating cost-minimal supply structures under the constraints of resource availability, the menu of given technologies, and the demand for useful energy. It estimates detailed energy systems structures, including energy demand, supply and emissions patterns, consistent with the evolution of primary and final energy consumption. GET is also a linear optimization model designed to choose primary energy sources, conversion technologies and transportation technologies that meet (in this version) a price elastic energy demand, at the lowest aggregate costs, subject to a carbon constraint (a tax or an emission cap). The GET model is now available on line at www.chalmers.se/ee/getonline. (In the web version of the model energy demand is exogenously given).

All three models permit the application of CCS to both fossil fuels and biomass. For this paper, all three models have been used to generate a range of stabilization scenarios for three different cases: the case where CCS is not used at all, that where CCS is only used for fossil fuels and that where CCS is used for both fossil fuels and biomass. Energy demand levels for electricity, transportation fuels and stationary fuel used in the business-as-usual case are roughly in line with those of the IPCC SRES B2 for all models (Nakicenovic and Swart 2000). All other factors in the model have not been harmonised, in order to compare the role of BECCS in the models under their default assumptions. An important factor in this context is the potential for bio-energy, this is discussed further in Section 4.

3 Results

Figure 1 shows the costs of the different stabilization scenarios as a function of the 2100 CO₂ concentration levels for the three different models. The cost is expressed as the net present value of future annual costs to meet the stabilization target using a discount rate of 5% (the discount rate is chosen for comparability with similar numbers in the Third and Fourth Assessment Report). The costs vary from 0–2.5 trillion US\$ up to 22.5 trillion US\$ for concentration targets approaching 300 ppm (MESSAGE and GET) and 360 ppm (IMAGE/TIMER). The costs estimates for the scenarios without CCS are consistent with results reported in the literature (Fisher et al. 2007).

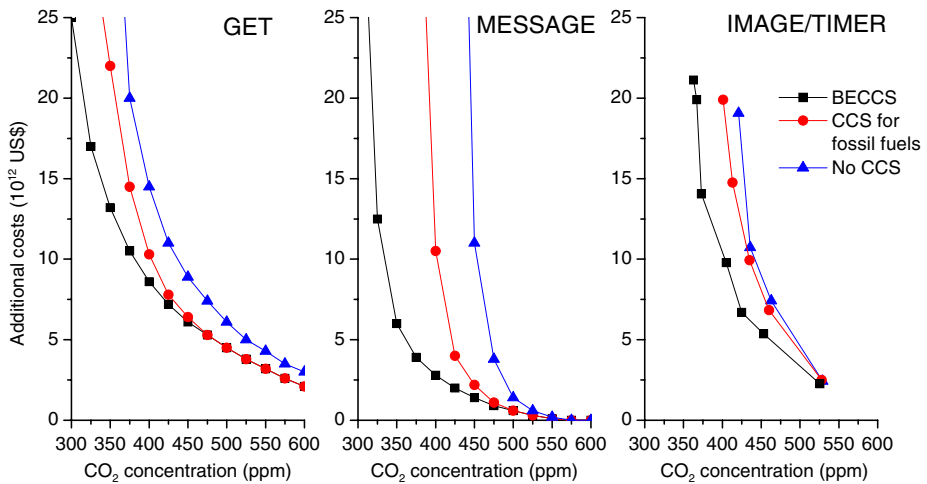


Fig. 1 Net present value costs for atmospheric CO₂ stabilization by the year 2100 by model. *Black lines* refer to a situation where BECCS is included, *blue line* with fossil CCS only, and *red line* with no CCS for the TIMER, GET, and MESSAGE models. Costs are expressed as the net present value of additional mitigation expenditures compared to the baseline (1990–2100) discounted at 5% in absolute amounts (trillions [10^{12}] of 2000 US dollars in market exchange rates)

From Fig. 1, it can be seen that the option of using CCS for fossil fuels reduces the cost of meeting most stabilization targets (see also the IPCC special report on CCS [IPCC 2005]). Further, it can be seen that BECCS makes it possible to meet lower concentration targets than what is attainable in the absence of BECCS or to meet a given target at a lower cost. For instance, the possibility to use BECCS reduces atmospheric concentrations by 50–100 ppm for the same cost. The potential contribution varies with the model used and depends on the stabilization target. The lower the stabilization target, the more significant the contribution to cost reduction obtained from BECCS. The reason is that it is only for low stabilization targets that the possibility of achieving negative global emissions becomes critical. The lower cost stems not only from the fact that BECCS makes it possible to meet the annual carbon constraint at a lower cost, but also from the fact that the introduction of BECCS changes the least-cost emission trajectory towards the atmospheric stabilization target so that less abatement takes place in the near term and more abatement occurs later in time. Postponing emission reductions increases the cumulative amount of carbon that we may emit over this century for any given concentration target (Wigley et al. 1996).

It is useful to compare the mitigation cost with expected future income (Azar and Schneider 2002). In most scenarios, future global income is an order of magnitude larger by the year 2100 than it is today. If compared to the net present value of future global income, the costs figures for the lowest stabilisations shown in Fig. 1 are around 2%.

When running the models with BECCS, we find attainability ranges for atmospheric CO₂ concentration as low as 300 to 360 ppm by 2100, with the highest of the scenarios approaching 350 ppm shortly after 2100. The reason that the three models depict different levels of attainable concentrations is related to underlying

assumptions and alternative modelling methodologies. In order to represent an illustrative range across models and scenarios, the underlying assumptions were not harmonized beyond principal energy drivers, such as the development of gross domestic product (GDP).

In Fig. 2, we present three energy scenarios (one from each modelling group) that demonstrate the technical feasibility of meeting a 350 ppm target around the year 2100. There is diversity in model results with some models relying more on non-biomass renewables, while others rely more on biomass, BECCS or nuclear. The contribution from fossil fuels with CCS is similar in all models. In all models, most of the emission reductions come from sources other than BECCS (renewables, energy efficiency, fossil CCS and nuclear). Finally, it may be noted that energy supply is around 50% higher in MESSAGE than in the other models. The lower primary energy supply in the GET and IMAGE/TIMER stems from the fact that these models are run with a price elastic energy demand.

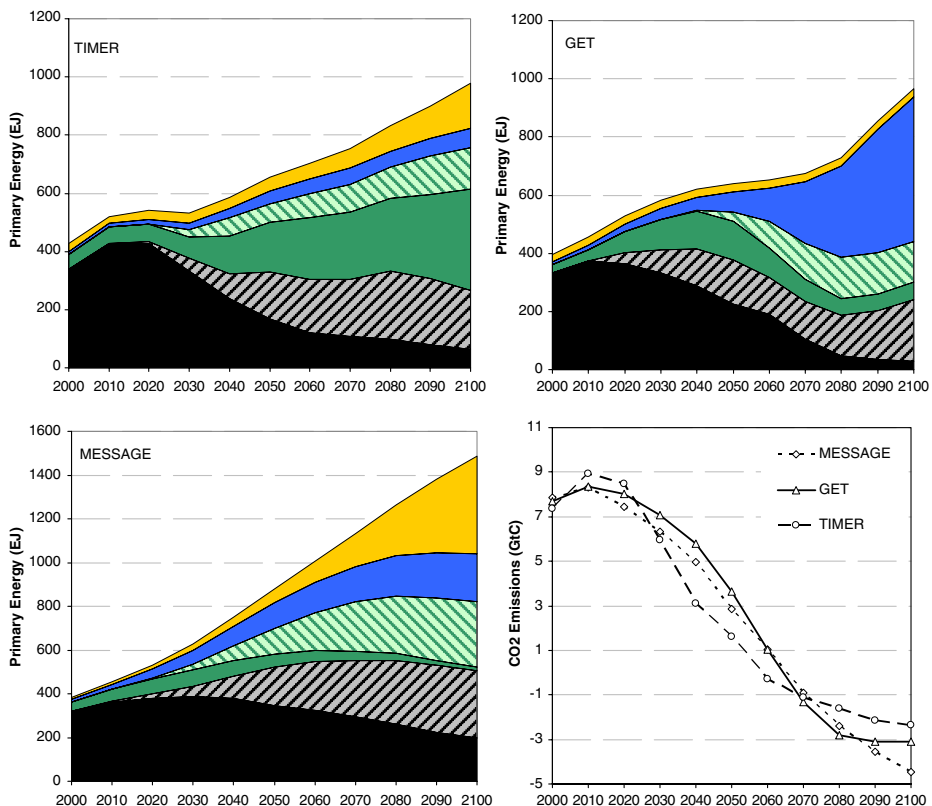


Fig. 2 Global development of primary energy carriers (exajoules per year) and CO₂ emissions (gigatons CO₂ per year) for scenarios aiming at the stabilization of atmospheric CO₂ at 350 ppm. **a–c** Show the contribution of nuclear (yellow), other renewables (blue), BECCS (green downward diagonal), bioenergy (green), fossil fuels with CCS (black upward diagonal), fossil fuels without CCS (black). **d** Gives the corresponding emission trajectories towards 350 ppm for the three models. GET and MESSAGE achieve a 350 ppm CO₂ concentration in 2100; the TIMER/IMAGE concentration amounts to 360 ppm and is expected to reach 350 ppm shortly after 2100

4 Discussion and conclusions

In all three models looked at, including BECCS allows for much lower targets to become attainable—and also at lower costs. In contrast, for less ambitious targets, including BECCS into the technology portfolio has hardly or even no influence on costs. This implies that BECCS (and for that matter CCS) can be considered, at this moment, as a pivotal technology in attaining low stabilisation targets. There are several critical issues, however.

One critical issue when assessing the potential role for BECCS is the potential supply of biomass. All modelling groups have made their own assumptions (so as to reflect a variety of different views). In our three model runs, 200–400 exajoules (EJ) of biomass per year is used throughout the period 2050–2100 (i.e., roughly 20–40% of the energy supply). This can be compared with values from the literature showing a wide range of biomass potential estimates. Literature estimates range from 50 to 675 EJ/year (Berndes et al. 2003). Part of the biomass can be obtained as residues from agriculture and forestry, which in our models is estimated at around 80–100 EJ/year. The remaining biomass, however, requires considerable areas of land for its production. For instance, 100 EJ/year may require 500 million hectares of land, if we assume an average biomass yield of 10 tons of dry matter per hectare annually (if all that biomass would be used in conjunction with CCS, some 2.5 GtC would be possible to capture on an annual basis). In different studies, van Vuuren et al. (2009) estimate the potential of bio-energy under different assumptions with respect to yields, sustainability criteria and land use conversion. Their results seem to indicate that potential may range in the order of 0–400 EJ until mid-century, but the higher numbers are only feasible under positive assumptions with respect to yields and assuming the use of natural grasslands (and thus loss of biodiversity). All-in-all, this implies that large areas of land may be required if BECCS is to make a significant contribution to the global carbon budget. Policies will need to be implemented to avoid biomass infringing on food security and other environmental goals (including the risk that a large scale expansion of biomass plantations may be established on forests or indirectly push the agricultural frontier into forests, and hence, cause huge releases of biospheric carbon as a negative side effect, see Tilman et al. 2009; Leemans et al. 1996; Searchinger et al. 2008; Persson and Azar 2010).

Another critical issue for our scenarios is the potential to store carbon from both fossil fuels and biomass. A recent IPCC assessment of the literature foresees storage capacity in geological formations of at least 550 GtC. The report notes uncertainties with respect to storage capacities in saline formations and emphasizes that the storage capacity might be significantly larger, in the order of 1,000s of GtC (IPCC 2005). Stored CO₂ over the course of the century as suggested by the scenario analysis here range between 350 to 500 GtC, which lies well within the global capacities reported above. However, much research remains before carbon storage can be applied at such scales. Surprises—physical or political—may appear that rule out the use of below-ground or ocean CO₂ storage. Currently, 1 megaton of CO₂ per year is stored in the Sleipner field in the North Sea. In order to realize the CCS scenarios as presented here, global storage activities must be some ten thousand times larger than at present. It cannot be taken for granted that there are sufficient and safe geological storage options, and sufficient political acceptability, for this technology to work at a large scale.

A final critical issue concerns the timing of mitigation. The option negative emission technologies—be it BECCS or the direct capture of CO₂ from the air (see Keith 2009)—makes it, from a purely physical point of view, possible to postpone emission reduction in the near term and compensate that by removing CO₂ some time later in the future and still meet the same concentration target in the end. However, we caution against using this possibility as an argument near term emission reductions. Continued business as usual emissions would lead to (higher) overshoots in the concentration level, leading to more climate impacts which might even be irreversible (O'Neill and Oppenheimer 2004; Lenton et al. 2008). In addition, it should be noted that the development of technologies like BECCS need a long lead time before large-scale deployment. It is likely to take around half a century before technological and social infrastructure for a global biomass energy system with CCS can be developed in order to make a significant impact on the atmospheric CO₂ concentration (in the order of reducing the concentration by 0.5–1 ppm CO₂/year).

For these reasons, near-term policies promoting both reduction of carbon emissions in the near term and the development of more advanced technologies that can achieve deeper cuts in emissions in the long term are required (see e.g., Sandén and Azar 2005).

Acknowledgements Financial support from the Swedish Energy Agency, Formas, Carl Bennet, IIASA GGI and the EU Project INSEA is gratefully acknowledged.

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